CORIOLIS MASS FLOW SENSOR

DESCRIPTION

5   CROSS-REFERENCE TO RELATED APPLICATIONS

[Para 1]   This application is a non-provisional of U.S.
Provisional Patent Application Serial Nos. 60/481,852 and
60/521,223, filed on January 2, 2004 and March 15, 2004,
respectively, which are incorporated by reference herein.

10

BACKGROUND

[Para 2]   The invention relates generally to a mass flow
measurement and control, and more particularly, to a mass
flow measurement and control device based on the Coriolis
15   force effect.

[Para 3]   Mass flow measurement based on the Coriolis force
effect is achieved in the following manner. The Coriolis force
results in the effect of a mass moving in an established
direction and then being forced to change direction with a
20   vector component normal to the established direction of flow.
This can be expressed by the following equation:

$$\vec{F}_C = 2\vec{M} \times \vec{\omega}$$

[Para 4]   Where

$$\vec{F}_C$$

25   (the Coriolis force vector) is the result of the cross product of

$$\vec{M}$$

(the momentum vector of the flowing mass) and

$\bar{\omega}$

(the angular velocity vector of the rotating coordinate system).

[Para 5]   In a rotating system, the angular velocity vector is
aligned along the axis of rotation. Using the "Right Hand
Rule", the fingers define the direction of rotation and the
thumb, extended, defines the angular velocity vector direction.
In the case of the typical Coriolis force flow sensor, a tube,
through which fluid flow is to be established, is vibrated.
Often the tube is in the shape of one or more loops. The loop
shape is such that the mass flow vector is directed in opposite
directions at different parts of the loop. The tube loops may,
for example, be "U" shaped, rectangular, triangular or "delta"
shaped or coiled. In the special case of a straight tube, there
are two simultaneous angular velocity vectors that are
coincident to the anchor points of the tube while the mass flow
vector is in a single direction.

[Para 6]   The angular velocity vector changes directions since,
in a vibrating system, the direction of rotation changes. The
result is that, at any given time, the Coriolis force is acting in
opposite directions where the mass flow vectors or the angular
velocity vectors are directed in opposite directions. Since the
angular velocity vector is constantly changing due to the
vibrating system, the Coriolis force is also constantly changing.
The result is a dynamic twisting motion being imposed on top
of the oscillating motion of the tube. The magnitude of twist
is proportional to the mass flow for a given angular velocity.

[Para 7]   Mass flow measurement is achieved by measuring
the twist in the sensor tube due to the Coriolis force generated

by a fluid moving through the sensor tube. Typical known devices use pick off sensors comprising magnet and coil pairs located on the flow tube where the Coriolis force's induced displacement is expected to be greatest. The coil and magnet
5 are mounted on opposing structures, for example, the magnet is mounted on the tube and the coil is mounted on the stationary package wall. The coil will move through the magnet's field, inducing a current in the coil. This current is proportional to the velocity of the magnet relative to the coil.

10 [Para 8]   In low flow applications, however, the tube is relatively small. This makes it difficult or impossible to mount sensing hardware on the tube itself. Prior art solutions to sensing the tube vibrations have been largely unsatisfactory. The present invention addresses shortcomings associated with
15 the prior art.

SUMMARY

[Para 9]   In accordance with aspects of the present disclosure, a Coriolis mass flow sensor includes a flow tube, a
20 light source, and a light pipe having a light inlet situated to receive light from the light source and a light outlet for emitting light received from the light source. A light detector receives light from the light pipe light outlet, and a drive device vibrates the flow tube such that the flow tube occludes
25 a light path between the light outlet of the light pipe and the light detector. In certain embodiments, the light pipe defines a generally square, or other polygon-shaped, cross section to scramble or "mix up" the light received from the light source to

achieve a more spatially uniform intensity distribution at the tube.

[Para 10] A sensing aperture having a predetermined shape is situated between the light outlet of the light pipe and the light

5   detector. The sensing aperture passes a portion of the light emitted from the light outlet of the light to the light detector, such that the light entering the light detector has the predetermined shape. The shape of the sensing aperture, and thus the light reaching the light detector, is a triangle in

10   exemplary embodiments.

[Para 11] The various components may be situated in one or more optics module bodies, which may define openings therein that receive the components. To achieve the desired package size, the openings may be oriented in various

15   directions, and mirrors and lenses may be employed to direct the light as necessary.

BRIEF DESCRIPTION OF THE DRAWINGS

[Para 12] Other objects and advantages of the invention will

20   become apparent upon reading the following detailed description and upon reference to the drawings in which:

[Para 13] Figures 1 and 2 are block diagrams conceptually illustrating a Coriolis mass flow controller and sensor in accordance with aspects of the present disclosure.

25   [Para 14] Figure 3 is a block diagram generally illustrating portions of a Coriolis mass flow device employing an optical pick off sensor in accordance with the present disclosure.

[Para 15]   Figures 4A and 4B are front and side sectional views, respectively, of the flow sensing portion of a Coriolis mass flow controller using an optical pick off sensor.

[Para 16]   Figure 5 is a perspective view of a Coriolis mass flow sensor in accordance with other aspects of the present disclosure.

[Para 17]   Figure 6 is a perspective view of an optics module body for a Coriolis mass flow sensor in accordance with additional aspects of the present disclosure.

[Para 18]   Figure 7 is a perspective view of a Coriolis mass flow sensor shown in Figure 5 with one optics module body removed.

[Para 19]   Figure 8 is an exploded view of one of the optics modules shown in Figure 5.

[Para 20]   Figure 9 is a sectional view of one of the optics modules shown in Figure 5.

[Para 21]   Figure 10 conceptually illustrates the sensing aperture of the Coriolis mass flow sensor shown in Figure 5.

[Para 22]   Figure 11 is a chart illustrating response curves showing linear response regions for exemplary flow tubes.

[Para 23]   Figure 12 is a chart showing the slopes of the curves illustrated in Figure 11.

[Para 24]   While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the description herein of specific embodiments

is not intended to limit the invention to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended
5 claims.

DETAILED DESCRIPTION OF THE INVENTION

[Para 25] Illustrative embodiments of the invention are described below. In the interest of clarity, not all features of
10 an actual implementation are described in this specification. It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-
15 related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

20 [Para 26] Figure 1 illustrates a Coriolis based mass flow sensor and controller in accordance with embodiments of the present invention. It is comprised of essentially two separate operational systems: a Coriolis sensor pick off and drive system A, and an application and control system B. The
25 Coriolis sensor pick off and drive system interfaces with the Coriolis sensor 1. The application and control system B provides an interface for a user 5, and provides control signals to a flow control device such as a valve 6.

[Para 27]   The purpose of the sensor pick off and drive system A is to control and sense the motion of the Coriolis sensor 1 for the purpose of determining relative mass flow as a function of Coriolis force, and relative density as a function of resonant
5   frequency.

[Para 28]   The exemplary sensor pick off and drive system A provides three data values to the application and control system B:

[Para 29]   *DeltaT* -- the time difference that relates to the
10   phase lag of one side of the sensor tube to the other indicating relative mass flow.

[Para 30]   *Frequency* -- the resonant frequency of the sensor tube that relates to the relative density of the measured material.

15   [Para 31]   *Temperature* -- an RTD is measured to determine the temperature of the sensor tube.

[Para 32]   The application and control system B uses *DeltaT* in conjunction with calibration constants to present the desired mass flow units to the user 5. It also uses *Frequency* in
20   conjunction with calibration constants to present the desired density and/or volumetric flow units to the user 5. *Temperature* is used for compensation of both mass flow and density calculations. The application and control system B uses the mass or volume flow unit output in comparison with
25   the user's set point input to control the valve 6 that regulates flow to the desired setting.

[Para 33]   Figure 2 is a block diagram conceptually illustrating portions of a Coriolis mass flow sensor as disclosed herein.

The Coriolis mass flow sensor 1 includes a flow sensor tube 2, with a drive device 3 situated relative thereto so as to vibrate the tube 2. Pick off sensors 4 are positioned relative to the tube 2 so as to measure the twist in the tube 2 due to Coriolis force.

[Para 34]   Mass flow measurement is achieved by measuring the twist in the sensor tube due to the Coriolis force generated by a fluid moving through the sensor tube. For example, in known Coriolis mass flow sensors, pick off sensors comprising magnet and coil pairs are typically located on the flow tube where the Coriolis forces induced displacement is expected to be greatest. The coil and magnet are mounted on opposing structures, for example, the magnet is mounted on the tube and the coil is mounted on the stationary package wall. The coil will move in and out of the magnet's field, inducing a current in the coil. This current is proportional to the velocity of the magnet relative to the coil. Since this is a velocity measurement, the velocity, and thus the signal, is at the maximum when the flow tube crosses its rest point (zero crossing). The Coriolis force induced twist causes a phase shift in the velocity signal that is detected by measuring the difference in the zero crossing times between the two velocity sensors. In practice this places a large accuracy burden on the time measurement circuitry. This may limit the ultimate sensitivity of mass flow measurement by this technique.

[Para 35]   U.S. Patent No. 5,555,190, assigned to the assignee of the present application, discloses digital signal processing methods and devices for determining frequency and phase relationships of a vibrating sensor tube such as the tubes

disclosed in conjunction with the Coriolis mass flow sensing devices disclosed herein. The entire specification of U.S. Patent No. 5,555,190 is incorporated by reference herein.

[Para 36]   Figure 3 illustrates an exemplary Coriolis mass flow
5   sensing device employing concepts disclosed herein. The illustrated Coriolis mass flow sensing device 500 includes, among other things, a flow tube 502 with a coil 513 situated near a magnet 514 to vibrate the tube 502. Light sources 510 are positioned on the sides near the top or on top of the flow
10   tube 502 where the displacement is expected to be the greatest. Photodiodes or other photo detectors 512 can then be placed on the opposite side of the tube 502 facing the light source 510. The photo detectors 512 are connected to sensor electronics that process the signals received from the photo
15   detectors 512. The sensor electronics may employ digital signal processing devices, such as the signal processing methods disclosed in U.S. Patent No. 5,555,190, or the lock in amplifier arrangement as disclosed in U.S. Patent Application No. 09/641,698, which is incorporated by reference. Other
20   embodiments are envisioned that use modal sensing or sinusoidal curve fit, wherein the received signal is compared to a reference using least squares phase determination, for example.

[Para 37]   In one specific embodiment, the light sources 510
25   and photo detectors 512 are part of an optical sense circuit implemented on an optical sense printed circuit board (PCB). The light sources 510 and photo detectors 512 comprise infrared LEDs and photodiodes to sense the motion of the sensor tube 502. As shown in Figure 3, there are two sets of

LEDs 510 and photodiodes 512, one set to sense each side of the sensor tube 502. In other embodiments, other types of light sources and detectors may be employed, using light of virtually any wavelength.

5   [Para 38] Figures 4A and 4B illustrate a Coriolis mass flow sensor 600 employing optical pick off sensors. The flow sensing portion 600 includes the flow sensor tube 602, to which a magnet 604 is attached. Infrared LEDs 606 and photodiodes 608 are coupled to an optical sense PCB 610,

10 positioned on either side of the flow sensor tube 602. The flow sensor tube 602, magnet 604, LEDs 606, photodiodes 608 and PCB 610 are all situated within a housing 612, to which a cover 614 is attached. A 1mH inductor functions as a coil 616 to drive the tube. The coil 616 is positioned outside

15 the housing 612.

[Para 39] Alternatively, the sensor tube 602, drive device 604,616 and pick off sensors 606,608 all may be contained within the housing 612, or selected components in addition to or in place of the coil 616 may be positioned outside the

20 housing 612. For example, certain embodiments may employ a housing 612 having a window defined therein. This allows the light source 606 and/or photo detector 608 to be placed outside the housing 612. In still further embodiments, the sensor electronics are remoted from the housing 612, for

25 example, using fiber optic cable. This may be desirable, for example, when the Coriolis mass flow sensing device is employed in a hazardous environment.

[Para 40] As disclosed above, the light source 606 and detector 608 may comprise an infrared LED matched to an

infrared photodiode. The size of the photodiode active surface is close to but slightly larger than the diameter of the sensor tube 602. As the tube 602 vibrates, it moves through the path between the LED and photodiode, occluding the light from the

5   LED. The tube 602 may be positioned so that the light path between the LED and detector is partially broken when the tube is at rest. As the tube moves about this rest position in a vibratory fashion, the light reaching the detector will alternately be at a minimum or maximum providing a

10   sinusoidal output from the detector. The relative outputs from each side of the tube can be measured for phase differences due to Coriolis induced flow effects.

[Para 41] An LED produces light with a specific intensity distribution. The distribution is known to be Gaussian -- the

15   light intensity decreases as the radial distance from the center of the light source increases. In other words, the light source is brightest in the center and gets dimmer towards the periphery of the light source. Thus, the intensity of the light reaching the photodiode varies not only in response to the

20   vibrating tube moving through the light path, but also based on the position of the tube relative to the light path. With the simple LED/photodiode arrangement illustrated in Figures 3 and 4, alignment of the tube is critical to accurately measure the twist in the flow sensor tube as peak to peak voltages must

25   be matched between the two sensors.

[Para 42] Such matching of the peak to peak voltages is difficult to achieve because the response is not linear. Only at specific points in the optical path will the two legs of the tube produce matching peak to peak voltages. This need to

precisely align the tubes can have the effect of lowering manufacturing yields and increasing manufacturing time and costs. If however, the response were linear, the two legs of the tube could be located anywhere in the linear region and the

5   peak to peak voltages would match.

[Para 43]   Other embodiments using optical sensing optimize the system to achieve a linear optical response. Among other things, the light emitted by the LED is conditioned to produce a flat power distribution. The image of the flow tube blocking

10   some of the light from the LED (shadow) is passed through a series of lenses and apertures. Figure 5 illustrates an exemplary Coriolis mass flow sensor 700 with such optical pick off sensors. The mass flow sensor 700 includes a base member 720 to which the flow tube 702 is attached. A drive

15   arrangement (not shown in Figure 5), such as a coil and magnet arrangement as shown in Figures 4A and 4B, is used to vibrate the tube 702. The optical pick off sensors are disposed in first and second optical module bodies 730. Figure 6 illustrates an alternative embodiment in which the two optical

20   bodies 730 are combined into a single optical body 731. Figure 7 shows the flow sensor 700 with one of the optical modules 730 removed to better show some of the components, such as the flow tube 702.

[Para 44]   An exploded view of one of the optical modules 730

25   is shown in Figure 8, and Figure 9 is a sectional view of the module 730 showing the components internal to the module 730. A light source, such as an LED 706, is disposed in a first opening 732 in the module 730. A light pipe 734 is situated in the opening 732 to receive light from the LED 706. A second

opening 740, which is oriented generally perpendicular to the opening 732, has a lens 738 is situated therein. A mirror 742 is positioned between the second opening 740 and a third opening 744 that is generally parallel to the first opening 732.

5　The third opening 744 defines a circular blocking aperture 746 and has a lens 748, a tube 750 and a disk 752 defining a sensing aperture 754 situated therein. A light detector, such as a photodiode 708, is also received in the third opening 744.

[Para 45]　The light pipe 734, or integrating bar, has a light
10　inlet 734a that receives light from the LED 706 and a light outlet 734b that emits the light. The light pipe 734 defines a generally square cross section that functions to scramble, or "mix up," the light by reflecting the light off the inside surfaces of the light pipe 734. This evens the brightness of the light
15　output by the LED 706, transforming the Gaussian optical output into a flat power distribution. The output of the LED 706 has a bright spot in the middle and is dimmer towards the outer edges, while the output of the square light pipe 734 is square with even brightness. In other embodiments, the light
20　pipe 734 may define cross-sectional shapes other than square. Almost any polygon (triangle, square, pentagon, etc.) will produce a much more uniform distribution than a circular light pipe. Other methods, such as diffusers, can also be used to produce a uniform light distribution.

25　[Para 46]　In the illustrated embodiments, the sensing aperture 754 is in the shape of a triangle. Accordingly, the light entering the photodiode 708 is in the shape of the triangle. The mirrors and lenses are configured to form an image of the tube, and the triangular sensing aperture 754 is located at the

image of the tube edge. The blocking aperture 746 is circular to provide a telecentric distribution of light rays striking the sensing aperture 754 and the detector 708.

[Para 47] The tube 702 is positioned such that, when it
5 vibrates, it moves through the light path established by the light emitted from the light pipe 734 -- the tube 702 creates a shadow 770 in the triangularly-shaped image, such that the light pattern at the detector 708 is an occluded image of the light source, as generally shown in Figure 10. The triangular
10 shape of the sensing aperture 754 allows a simple calculation of the power entering the photodiode 708. Throughput (*T*) is the ratio of the power not blocked by the tube 706 to the total power entering the photodiode 708, which reduces to the ratio of the area of the sensing aperture not blocked by the tube
15 (*A*$_{nb}$) to the total area of the triangle (*A*$_{tot}$):

$$T = \frac{A_{nb}}{A_{tot}}$$

[Para 48] As the tube 702 moves in one direction, the throughput increases, and as it moves in the opposite direction the throughput decreases. This motion generates a sine wave
20 with a peak to peak voltage which must match for each leg of the tube. The peak to peak voltage is directly related to the slope of T as a function of y in Figure 11. Since this is by definition linear the slope is constant. Therefore, the peak to peak voltage can be matched as long as both legs of the tube
25 are located such that the values of y range from the tube diameter to the triangle height.

[Para 49] Figure 11 shows two response curves: curve 801 is for a 100 gram per hour tube having an outside diameter of

0.3mm, and curve 802 is for a 3,000 gram per hour tube
having an outside diameter of 0.8 mm, with the triangular
aperture 754 having a height of 1.5 mm. Figure 12 shows the
slopes of the response curves 801, 802. As shown in Figures
5   11 and 12, the slopes of the curves 801, 802 are constant in
the linear response regions 811, 812 of the curves. Thus, it is
not necessary for the two legs of the tube to be located at
exactly the value of y where the peak to peak voltage will
match. The two legs of the tube need only be located in the
10   linear response range as described above. For the 100 gram
per hour tube (curve 801), with on leg of the tube located in
the allowed range, the opposing leg can be located anywhere
within the optical path from the tube diameter (0.3 mm) to the
triangle height (1.5 mm). The allowed manufacturing range is
15   thus 1.5 – 0.3 = 1.2mm.

[Para 50]   Other sensing arrangements are contemplated. For
example, a square sensing aperture could be employed. Two
light detectors may be used side by side, wherein the light
reaching the respective detectors will vary with movement of
20   the tube.

[Para 51]   The mirrors and lenses allow the components to fit
into the desired package size. Figure 9 generally shows the
light path through the module body 730. Light from the LED
706 enters the light inlet 734a of the light pipe 734. As noted
25   above, the sides of the light pipe 734 mix the light to achieve a
square, even intensity pattern. In the illustrated embodiment,
the light outlet 734b is angled and polished so that it functions
as a mirror to change direction of the light. As shown, for
example, in Figure 7, a turning mirror 772 is situated between

the first and second openings 732,740 to direct the light into the second opening 740. The tube 702 is positioned between the light outlet 734b and the turning mirror 772 so that the tube 702 moves through the light path established by the light

5 emitted from the light pipe 734. In the embodiment shown in Figure 6, the turning mirrors 772 are integrated into the module body 731.

[Para 52] The turning mirror 772 directs the light into the lens 738 situated in the second opening 740. The mirror 742

10 directs the light from the second opening into the third opening 744. The blocking aperture 746 blocks stray light to maintain to the square, even density. The light passes trough the lens 748 and the sensing aperture 754 and is received by the photodiode 708. The lenses 738, 748 and the blocking

15 aperture 746 function to maintain a magnification of 1:1.

[Para 53] The LED 706 and photodiode 708 are connectable to electronics outside the module body 730, allowing the electronics to be located at a distance from the optics. This facilitates use in environments that may be hazardous to the

20 electronics. In other embodiments, the LED 706 and photodiode 708 are also located remotely from the module body 730 with fiber optics links connecting them to the passive optics components located in the module body 730. This allows use in high temperature applications, for example.

25 [Para 54] The particular embodiments disclosed above are illustrative only, as the invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details

of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are considered within the scope and spirit of the invention. Accordingly, the protection sought herein is as set forth in the claims below.